

[54] **DEVICE AND PROCESS FOR
MAGNETO-GRAVIMETRIC PARTICLE
SEPARATION USING NON-VERTICAL
LEVITATION FORCES**

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209/232, 209/39**

[51] Int. Cl. **B03c 1/30**

[58] Field of Search 209/1, 214, 172, 172.5, 215,
209/2, 223, 232, 39; 310/10, 11; 250/49.1 ME

[56] References Cited

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[57] ABSTRACT

A volume of magnetic fluid is caused to function as a density spectrograph by impressing a magnetic field upon the fluid in an orientation such that non-vertical levitation forces are developed upon particles immersed in the fluid. Particles are separated according to their density by passing them through the magnetic fluid. Interaction of particles within the fluid with the vector sum of gravitational and levitation forces causes each particle to travel a trajectory through the fluid characteristic of its density. Particles exit from the fluid at different locations, according to their density, thus allowing collection of density-graded fractions.

18 Claims, 3 Drawing Figures

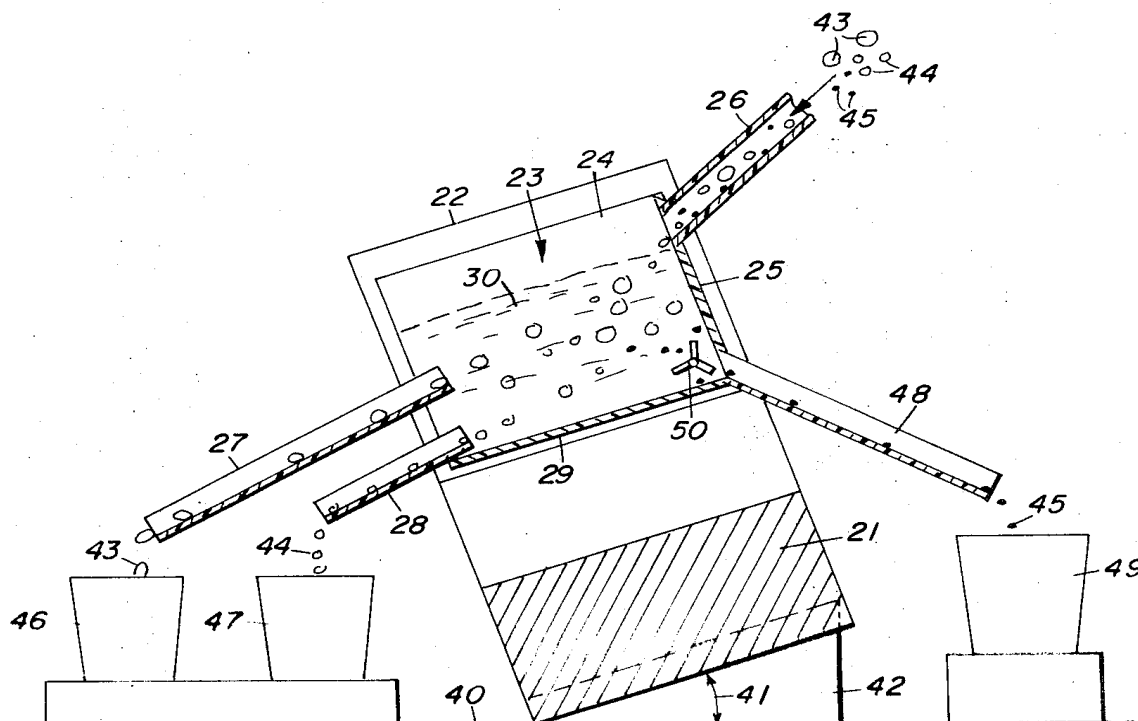


FIG. 1

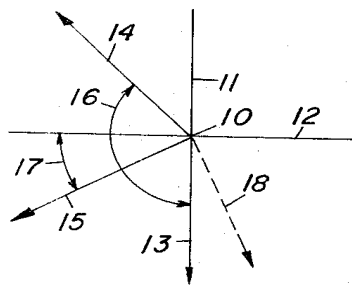


FIG. 2

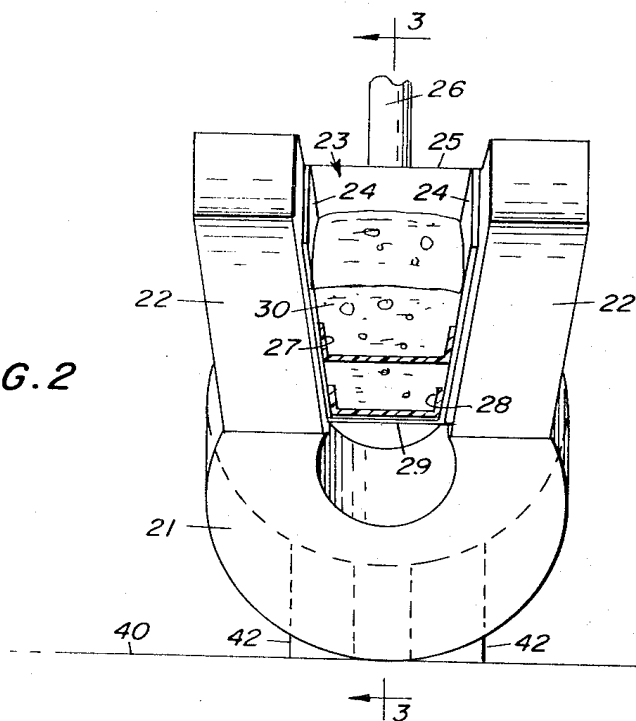
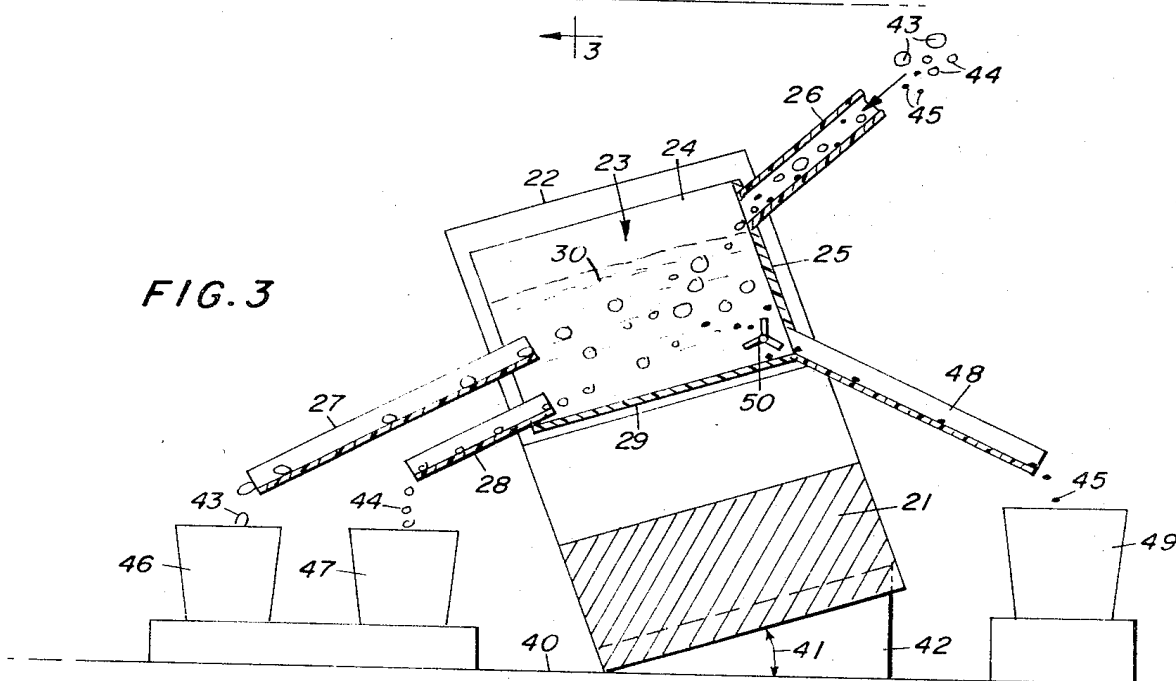


FIG. 3



DEVICE AND PROCESS FOR MAGNETO-GRAVIMETRIC PARTICLE SEPARATION USING NON-VERTICAL LEVITATION FORCES

BACKGROUND OF THE INVENTION

Magnetic fluids, sometimes referred to as "ferro-fluid" in the art, are Newtonian liquids which retain their fluidity in the presence of external magnetic fields and field gradients. The fluids are ultrastable colloidal suspensions of submicron-sized, ferro- or ferrimagnetic particles in liquid carriers such as hydrocarbons, particularly paraffinic hydrocarbons such as kerosene, silicones, fluorocarbons and the like. A definitive test which characterizes magnetic fluids in their super paramagnetic behavior shown by the absence of a hysteresis loop in their magnetization curves. The magnetization curve of a magnetic fluid is in appearance a symmetrical, sigmoid curve about the origin. Magnetic fluids may be prepared by the method of Papell (U. S. Pat. No. 3,215,572) or by the method disclosed and claimed in copending, commonly assigned application Ser. No. 148,206.

It was Rosensweig who discovered that antigravity or levitation forces can be developed within a magnetic fluid when the fluid is placed in a magnetic field. Since that time, numerous applications of this phenomenon have been developed. Kaiser in U. S. Pat. No. 3,483,968 discloses the separation of particles having differing densities by introducing them into a magnetic fluid which is subjected to the influence of a controlled magnetic field. Kaiser achieves either sequential or differential levitation of particles within the field by orienting the magnetic field gradient in a vertical direction opposite to gravity. Rosensweig, in U. S. Pat. No. 3,483,969, discloses another technique for separating particles by density. He utilizes a body of a magnetic fluid as a horizontal sieve in which a levitational force opposite in direction to gravity is maintained within the fluid while the levitational force progressively decreases in magnitude along the horizontal. Similar techniques have been used by others in devices for determining particle density by measurement of the magnetic field strength necessary to levitate a particle. All of these prior art techniques have one attribute in common, all utilize the magnetic levitation force in opposition to gravity.

SUMMARY OF THE INVENTION

We have found that particles may be separated according to their density in a continuous fashion by utilizing a volume of magnetic fluid as a density spectrograph. We achieve this result by orienting the magnetic levitation force in a non-vertical, and most preferably in a nearly horizontal direction. Forces acting on a particle immersed in the magnetic fluid then comprise the vector summation of the non-vertical magnetic levitation force and the vertical gravitational force thus causing each particle to follow a pre-defined trajectory through the fluid according to its density. Particles of differing densities are collected separately at the points where they exit from the magnetic fluid. Additionally, magnetic particles are deflected by the field interaction in a direction opposite to that of nonmagnetic particles. Thus, our device has the additional capability of performing (within limits) a magnetic-nonmagnetic separation

simultaneously with density separation of the nonmagnetic particles. The proportion of magnetic to nonmagnetic particles must be sufficiently small to avoid any substantial change in the magnetic field gradient within the pole gap. Our technique is generally applicable to the separation of all particulate nonmagnetic materials which do not react with nor dissolve in the magnetic fluid. Likewise, our technique is generally applicable to the separation of magnetic from nonmagnetic particles.

It is an object of our invention to provide a method and means for the continuous magnetogravimetric separation of particulate materials.

Another object of our invention is to provide a density spectrograph for the continuous separation of particles.

Still another object of our invention is the assorting of particulate materials by subjecting the particulates to the influence of a combined gravitational and non-vertical levitation force as they pass through a volume of magnetic fluid.

DETAILED DESCRIPTION OF THE INVENTION

Our process and apparatus are illustrated by the following drawings:

FIG. 1 is a force diagram showing the orientation of force vectors acting on particles during their passage through the magnetic fluid.

FIG. 2 is a front, partial-sectional view of an apparatus embodying the principles of the invention.

FIG. 3 is a side, sectional view of the apparatus illustrated in FIG. 2.

The basic purpose of this invention is to provide means and methods for the magneto-gravimetric separation of particles by use of non-vertical levitation forces impressed upon a magnetic fluid. This approach allows the continuous separation of materials which have differing densities by means of a single magnetic fluid-magnetic field combination. The fluid acts as a density spectrograph diverting particles in differing trajectories according to their density. An additional important advantage resides in the behavior of magnetic particles under these conditions. Magnetic particles are deflected in a direction, or along a trajectory, opposite to that of nonmagnetic particles. Magnetic particles cannot be easily separated in the prior art "float or sink" approach using magnetic fluids.

When a non-uniform magnetic field is allowed to interact with a magnetic fluid, there is throughout the fluid mass an inwardly directed force or pressure. A nonmagnetic body immersed within the magnetic fluid will be acted on by that force and, if that force or pressure is sufficient to overcome gravity, the nonmagnetic body will be buoyed to the surface of the fluid. In practice, it has been possible to levitate platinum (specific gravity 21.4) in a magnetic fluid having a specific gravity less than 1. Prior art approaches to materials separation have relied upon adjustment of the magnetic field to preferentially or sequentially levitate one or more components of the materials mixture according to their densities.

Our invention differs from those past approaches in that we do not utilize the magnetic fluid to levitate particles but instead orient forces acting upon a particle immersed in the magnetic fluid so as to cause the fluid to act as a density spectrograph. This effect will be better understood by reference to FIG. 1 which is a vector

diagram of forces acting upon a particle within the magnetic fluid. Assume that a particle is located at origin 10 which is intersection of vertical axis 11 and horizontal axis 12. There will always be a gravitational force acting on the particle in a vertical downward direction indicated by vector arrow 13. Interaction of a magnetic field with the magnetic fluid will produce another force vector, called the levitation force, whose direction may be altered at will. The levitation force will always be in a parallel but opposite direction to the magnetic field gradient. This levitation force is represented in the drawing as vector arrow 14. Since the levitation force is oriented in a non-vertical direction, the resultant force acting upon a particle within the fluid is the vector sum of the gravitational and levitational forces and is represented by vector arrow 15.

Angle 16 is the angle between the vector direction of the levitational force. (or the magnetic field gradient) and the vertical and must be less than, preferably substantially less than, 180° . If angle 16 were to be made 180° , then the conventional "float-or-sink" levitational techniques would prevail. We prefer to set angle 16 at values ranging from about 90° to 175° . It is possible but less convenient to operate at angles less than 90° , but of course substantially greater than zero. Angle 17 is the deflection angle measured from the horizontal and this angle is dependent upon the density of the particle being acted upon by the combined forces as may be shown by a mathematical analysis of the acceleration in both the horizontal and vertical directions. A mathematical expression relating density to deflection angle has been derived but this expression cannot be solved explicitly for the magnitude of the angle. However, by the method of successive approximations and reiterations to consistency, performed with the aid of a computer, we determined that calculated values of the particle displacement agreed closely with experimentally observed values.

In one such experiment, the levitation force was oriented along the horizontal and a magnetic fluid having a density of 0.96 g/ml and viscosity of 2.72 cp was positioned between the constant gradient pole pieces of an electromagnet. the magnitude of the magnetic field gradient was measured to be 0.3 koe/cm and the average magnetic moment per unit volume of the fluid at the ambient magnetic field was 7.7 erg/oe cm^3 , which corresponds to an average fluid magnetization of 96.7 gauss. Objects of differing densities were fed through the magnetic fluid and were received on a filter paper positioned in a plane 15.6 cm below, or 18.4 cm from the center, of the fluid. Results obtained are as follows:

TABLE I

Sample	Density g/cm	Angle of deflection	Displacement, cm	
			Experi- mental	Calcu- lated
Glass	2.50	74.5°	4.87 ± 0.30	4.95
Aluminum	2.70	77.0°	3.96 ± 0.37	4.23
Alumina	3.84	81.5°	2.71 ± 0.30	2.70
Lead	11.34	88.0°	0.57 ± 0.13	0.64

All of those materials used in the experiment were non-magnetic. Magnetic materials, such as iron, when passed through the magnetic fluid are deflected in an opposite direction corresponding to vector arrow 18 on FIG. 1.

Turning now to FIG. 2, there is shown a front, partial-sectional view of an apparatus embodying the princi-

ples of our invention. In this embodiment, the magnetic field is provided by a permanent magnet 21 such as the large horseshoe type shown. Placed on the poles of the magnet are pole pieces 22 which geometrically define and localize the magnetic field produced by magnet 21. Supported between the pole pieces is cell 23 constructed of a nonmagnetic material. Cell 23 comprises side walls 24, back 25, feed entry tube 26, exit chutes 27 and 28 and bottom 29. Except for exit chutes 27 and 28, the front of the cell is unobstructed. Placed within the cell is a volume of magnetic fluid 30. It is important to note that cell 23 is not necessary to contain magnetic fluid 30 within the magnetic field defined by pole pieces 22.

In operation, particles to be separated are introduced into magnetic fluid 30 via feed tube 26 where the particles come under the influence of both gravitational and non-vertical levitation forces. Under these combined forces, particles travel different trajectories through the fluid depending upon their densities. In the apparatus illustrated, particles exit from the front of cell 23 via chutes 27 and 28 which direct the separated particle streams into appropriate receptacles. Since the least dense particles display the smallest deflection angle (as defined in FIG. 1) they will exit near the top of the cell or along chute 27. Denser particles will exit from the cell at lower levels or along chute 28. The apparatus illustrated will make a two-way, or heavy-light, split. It is possible to simultaneously collect one or more intermediate density fractions by adding additional fraction collecting chutes between chutes 27 and 28 and by otherwise changing the geometry of the cell as will be apparent.

FIG. 3 generally represents a side-sectional view of the apparatus of FIG. 2 taken along line 3-3 of that drawing. Line 40 represents a horizontal reference plane. The entire apparatus is tilted forward to form an angle 41 with the horizontal. Relating angle 41 to angle 16 of FIG. 1, angle 16 is equal to 180° minus angle 41. Element 42 comprises means to support the apparatus in a non-vertical position and may be a wedge or clamp and is preferably adjustable to allow angle 41 to be varied over a range of about 15° to 90° .

More fully illustrating operation of the device, the particle stream entering through feed tube 26 consists of particles 43 of light density, particles of greater density 44 and magnetic particles 45. Particles 43 and 44, being nonmagnetic, are diverted along differing trajectories toward the front of the cell and exit from the magnetic fluid by way of chutes 27 and 28 respectively. Receptacles 46 and 47 of any convenient type are provided for collection of the two fractions. Magnetic particles 45 are accelerated along a trajectory opposite in direction to the nonmagnetic particles and can be mechanically removed from the pole surface by way of chute 48 to be collected in receptacle 49. A scraper or paddle wheel 50 may be provided to detach magnetic particles from the pole surface and direct them into chute 48. Since particles exiting from the magnetic fluid will ordinarily carry small quantities of fluid as a coating, the level of magnetic fluid in the device will soon be depleted. Means are provided (not shown on the drawings) to add make-up magnetic fluid to the device on either an intermittent or continuous basis. Particles may be conveniently introduced into the device by use of a vibratory feeder.

Our method and apparatus is generally applicable to the separation of any particulate mixtures whose components have a higher specific gravity than that of the magnetic fluid and which are nonsoluble in and non-reactive toward the magnetic fluid. Since a number of different types of liquids may be used as a magnetic fluid base, it is usually possible to select an appropriate magnetic fluid for any mixture of particulates. We can control the cut-point between density fractions in a variety of ways in order to produce product streams of any desired density range. This may be done by changing the number and/or spacing of the particle exit chutes; by changing the angle between the levitational force vector and the vertical; by changing the magnetic field strength and/or the magnetic field gradient; by changing the value of the saturation magnetization of the magnetic fluid or by combinations of these techniques. We have found that average magnetic field gradients in the range of about 0.1 to about 3 kilo-oersted per centimeter are appropriate for use in our invention. Generally, the higher values find application when separating materials of high specific gravity.

Magnetic fluids which we have found to be most useful for ordinary separations are those having a hydrocarbon base such as kerosene. These fluids combine economy, low viscosity, low volatility, general chemical inertness and water immiscibility; all desirable properties in most materials separations. Magnetic fluids having a saturation magnetization ranging from about 50 to 500 gauss are preferred but fluids with even higher or lower values of saturation magnetization are operative. Magnetic fluids may be removed from separated particles by slurring the coated particles in water. This technique is particularly adapted to those magnetic fluids having a specific gravity less than 1 since the magnetic fluid will then float on the water where it can be recovered and reused. It is often advantageous to warm the water, used to recover the magnetic fluid, to a temperature within the range of about 40° to 90°C. A faster and more complete removal and separation of the magnetic fluid from the particulates is thus achieved. In some cases, we have found it advantageous to pretreat particulates before separation in order to reduce magnetic fluid losses. This pretreatment consists of coating or saturating the particulates with a material or liquid which the magnetic fluid will not wet. In the case of many materials, the pretreatment may consist simply of wetting the particulate with water prior to separation.

Within a relatively broad range, size of the particles being separated has little if any effect on the process. Maximum particle size, however, must be relatively small compared to the volume of magnetic fluid suspended within the magnetic field. In practical terms, this places an upper particle size limit of about $\frac{1}{4}$ inch. The lower particle size limit is determined by that point at which settling velocity of the particle within the fluid is significantly slowed. This in turn depends upon particle shape and specific gravity as well as upon particle size and fluid viscosity. It is preferred to operate our process using a particulate feed of a size range such that essentially all particles will pass a $\frac{1}{4}$ inch screen and will be retained by a 100 mesh screen. In general, best results are obtained using a feed having a relatively narrow size range.

The following examples will more completely illustrate the capabilities of our invention.

EXAMPLE 1

An apparatus, similar in construction to that illustrated in FIGS. 2 and 3, was used for the continuous separation of alumina balls (specific gravity 3.8) from lead shot (specific gravity 11.3). A laboratory magnet, of the permanent horseshoe type, was used to provide the magnetic field and was oriented such that the angle between the direction of the levitation force and the vertical was approximately 160°. The mixture was poured into the magnetic fluid and was thereby separated into two fractions as the particles exited from the fluid along different trajectories. An essentially complete separation of alumina from lead was obtained.

EXAMPLE 2

Apparatus generally similar to that used in Example 1 was used to separate a non-ferrous metal fraction obtained from the residue of an experimental municipal waste incinerator. Since the particular apparatus used in the experiment had not been fitted with means to continuously remove magnetic particles, the sample was first passed through a conventional magnetic drum separator. The fraction was screened and that portion passing 4 mesh and retained by 14 mesh was used in the experiment. This portion had a specific gravity of 4.3 and had the following analysis: aluminum, 51.1%; copper, 27.6%; zinc, 13.4%; lead, 2.7% and iron, 2.0%.

A permanent magnet was used to provide the magnetic field and the magnetic fluid used had a saturation magnetization of 80 gauss. The direction of the levitation force was then adjusted by experimental positioning of the magnet to provide a 2-way, heavy-light split with all particles having a specific gravity less than 4.0 being collected in the light fraction. A continuous flow of the sized residue was supplied the separator using vibratory feeder. A light and a heavy fraction were continuously collected in water filled containers as the particles exited from the magnetic fluid. Most of the magnetic fluid, retained on the surface of the particles, separated from the particles and floated on the top of the water where it was collected and recycled to the separator. The particles were further cleaned by sweeping adhering fluid up into the water by use of a small magnet.

The light fraction made up 58 percent by weight of the feed, had a specific gravity of 2.9, and had the following analysis: aluminum, 84.7%; copper, 3.2%; zinc, 4.9%; lead, 0.6%; and iron, 1.6%. The heavy fraction had a specific gravity of 8.1 and had the following analysis: aluminum, 2.8%; copper, 60.6%; zinc, 27.2%; lead, 1.8% and iron 1.7%.

A second separation was performed on the heavy fraction to obtain a zinc-rich portion and a copper-brass portion. This second separation was performed on a different apparatus in that an electromagnet was used to provide the magnetic field rather than a permanent magnet. The electromagnet had a 1 inch pole piece gap and was adjusted to provide a field gradient of 0.13 koe/cm. The magnet was positioned so as to orient the levitation force at an angle of about 105° with the vertical. Using a magnetic fluid having a saturation magnetization of 215 gauss, these settings provided a heavy-light split at a specific gravity value of 7.2.

The light, or zinc-rich portion, contained 20 percent by weight of the starting material, had a specific gravity of 6.8 and had the following analysis: aluminum, 6.2%;

copper, 11.4%; zinc, 67.7%; lead, 1.6% and iron 2.8%. The copper-brass portion had a specific gravity of 8.8 and had the following analysis: aluminum, 0.6%; copper 72.6%; zinc, 17.3%; lead, 4.7% and iron, 0.9%.

We claim:

1. A method for the continuous magnetogravimetric separation of particles according to their density which comprises:

passing a mixture of particles having differing densities downwardly through a volume of magnetic fluid while subjecting the magnetic fluid to the influence of a non-uniform magnetic field having an orientation such that a non-vertical levitation force is produced upon a solid immersed in the fluid whereby interaction of the levitational force and gravity cause each particle to traverse the fluid in a trajectory characteristic of its density, and, collecting fractions of differing densities as the particles emerge from the fluid.

2. The method of claim 1 in which the angle between the vector direction of the levitation force and the vertical is less than 175° but greater than zero.

3. The method of claim 2 wherein said angle is in the range of 90° to 175°.

4. The method of claim 3 wherein the magnetic fluid has a saturation magnetization in the range of 50 to 500 gauss.

5. The method of claim 4 wherein the magnetic field gradient is in the range of about 0.1 to 3 kilo-oersted per centimeter.

6. The method of claim 5 wherein the particles being separated have a size range such that they will pass a ¼ inch screen and will be retained on a 100 mesh screen.

7. The method of claim 5 wherein the particles are nonmagnetic.

8. The method of claim 7 wherein the fractions of differing density are immersed in water thereby causing magnetic fluid adhering to the surface of the particles to separate from the particles.

9. The method of claim 8 wherein the separated magnetic fluid is recycled to the volume of magnetic fluid which is subjected to the influence of the magnetic

field.

10. The method of claim 8 wherein the water is at a temperature in the range of about 40° to 90°C.

11. The method of claim 6 wherein the particles are treated, prior to the separation step, with a material which the magnetic field will not wet.

12. The method of claim 6 wherein the magnetic field is produced by a permanent magnet.

13. The method of claim 6 wherein the magnetic field is produced by an electromagnet.

14. A device for the continuous magnetogravimetric separation of particles according to their density which comprises:

means to produce a non-uniform magnetic field;

15 a volume of magnetic fluid within said magnetic field;

means to orient the gradient of said magnetic field in a non-vertical direction thereby orienting the levitation force, produced on a solid immersed in the fluid, in a parallel but opposite non-vertical direction;

means to introduce a mixture of particles having differing densities downwardly into an upper portion of said magnetic fluid, and

25 means at a lower portion of said magnetic fluid to collect at least two density-graded fractions of said introduced particles as they emerge from the fluid.

15. The device of claim 14 wherein the gradient of the magnetic field is oriented in a direction such that the angle between the vector direction of the levitation force and the vertical is less than 175° but greater than zero.

16. The device of claim 15 wherein said angle is in the range of 90° to 175°.

17. The device of claim 16 wherein the magnetic fluid has a saturation magnetization in the range of 50 to 500 gauss.

18. The device of claim 17 wherein the magnetic field gradient is in the range of about 0.1 to 3 kilo-oersted per centimeter.

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